EVALUATION AND DESIGN OF RAINGAUGE NETWORK IN BURHI GANDAK SUB-BASIN

आपो हि ष्ठा मयोभुवः

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PREFACE

Hydrological and meteorological data are collected mainly to provide information for assessing, developing and managing the water resources. The aim of a hydrological network is to provide a density and distribution of stations in a region such that by interpolation between data sets at different stations, it should be possible to determine with sufficient accuracy, the characteristics of meteorological and hydrological elements anywhere in the region.

A network of raingauges are intended to serve general as well as specific purposes such as water supply, hydropower generation, irrigation and flood control. For planning, a network to meet these requirements, scientific approach is necessary. Several authors have suggested simple and rigorous statistical techniques like estimation of error in the computed aerial rainfall and optimum interpolation techniques like objective analysis and Kriging.

A case study for network design of raingauge in different flood affected basins of Bihar has been undertaken by Ganga Plains Regional Centre of the National Institute of Hydrology. As first part of this study, Burhi Gandak sub-basin of Ganga basin has been selected and the evaluation of existing network of raingauges using world meteorological Organization (WMO) criteria, $(C_v/P)^2$ technique, Kagan's technique for raingauge network on the basis of coefficient of spatial variation of rainfall and the expected error in the estimation of aerial rainfall and Hall's technique for key station network for the purpose of flood forecasting have been carried out and presented in this case study.

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ABSTRACT

For proper management development and assessment of water resources, hydrological and meteorological data are collected. Rainfall is one of the most basic data required for correct assessment of water resources. The aim of raingauge network is to provide the number and location of raingauge stations in a region such that by interpolation between data sets at different stations it should be possible to determine with sufficient accuracy the rainfall depths in the region.

A network of raingauge stations is intended to serve more than one purpose such as water supply, hydropower generation, irrigation, flood forecasting, flood control etc. To meet these requirements, the network design should be appropriate to the target and proper scientific approach is necessary. Several authors have suggested simple and rigorous statistical techniques like estimation of error in the computed areal rainfall and optimal interpolation techniques like objective analysis and Kriging.

Burhi Gandak catchment has an area of 10,150 sq. km. in Bihar with a network of 15 raingauges. The catchment experiences extreme floods during monsoon season. A good network of raingauge stations is therefore, necessary for planning relief measures and future flood management schemes.

Also, an adequate network of ordinary and self-recording raingauges is necessary for providing good data base for drainage schemes, operational flood forecasting and river management. The State Irrigation Department had indicated interest in scientific assessment of present network and to determine the need of the augmentation of the raingauge network for water resources assessment and flood forecasting purposes in the catchment and other areas.

A network design study of the raingauges in the Sub-basin has been undertaken keeping in view the requirement of raingauges. Besides the WMO standard and simple well known formula N= $(Cv/P)^2$ and the kagan's technique involving the interstation correlation, Hall's rational method for determining the key station network has also been used to determine the number of raingauges required for climatological and hydrological considerations in the Sub-basin.

The results indicate that in general the existing network seems to be adequate from climatological considerations but for hydrological purposes at least one or two raingauges should be of self recording type. $(Cv/P)^2$ and Kagan's technique have yielded comparable results.

This case study has also indicated that for designing the raingauge network for hydrological purposes appropriate accuracy criteria needs to be laid down and the area based WMO criteria need not be the only guideline.

1.0 INTRODUCTION

1.0 Introduction

Most hydrological variables such as rainfall, streamflow or groundwater have been used for many years by separate official bodies, private organisations, but there has been very little logical design in the pattern of measurements. The installation of gauges for rainfall and streamflow has usually been made to serve a single, simple purpose. Nowadays, with the growth of population and the improvement in communication, the observation, collection, compilation and analysis of hydrological and hydrometeorological data are considered essential for the development and management of water resources. Rainfall is one of the basic data required for correct assessment of water resources. Estimation of the number and location of the raingauge stations which will provide sufficient information regarding rainfall over the catchment, is referred to as Network design. It is, therefore, necessary to ensure that the raingauge network is adequate, such that by interpolation of the data at different raingauge stations, it may be possible to determine the rainfall depths in the region with desired accuracy.

A network of raingauge station is intended to serve more than one purpose, such as water supply, hydropower generation, irrigation, flood forecasting, flood control etc. There are considerable variations in hydrological and hydrometeorological variable with time and the level of information required changes in tune with the level of development in the region. Therefore, the network should be capable enough to meet the requirements.

Burhi Gandak catchment(Bihar) having an area of 10,150 sq. km, is situated on the left bank of the Ganga river and lies between the Gandak river system on the west and the Bagmati river system on the east. The Burhi Gandak catchment has a network of 15 raingauges. The State irrigation Department has indicated its interest in the augmentation of the raingauge network for providing better estimates of aerial rainfall for operational purposes during the flood and other hydrological analyses. This study has been under taken to design the network of raingauges in the Burhi Gandak catchment by utilising the available rainfall data of the existing raingauges upto 1990, provided by Bihar State Irrigation Department.

2.0 REVIEW

2.0 Review

The aim of the optimum rain-gauge network design is to obtain all quantitative data averages and extremes that define the statistical distribution of the hydrometeorological elements, with sufficient accuracy for practical purposes.

Rainbird (1965) had discussed the problem of network design of precipitation stations and suggested an over view of the problem by assessing the accuracy of data required, the relative importance of precipitation data for the project and time intervals for which such records need be maintained for a given region.

Rodda (1969) has termed a hydrological network as a programme for systematically acquiring the requisite information.

The minimum network densities for hydrometeorological practices as recommended by world meteorological Organisation (1974) are

i. For flat regions of temperate, mediterranean and tropical zones- One station for 600-900 sq. km.

ii. For mountainous regions of temperate, Mediterranean and tropical zones- One station for 100-250 sq.km.

iii. For arid and polar regions- One station for 1500-10000 sq. km. depending on feasibility.

The recommendation of Indian standards Institute (ISI 4987-1968) are as follows :

i. One raingauge upto 500 sq. km. might be sufficient in non orographic regions.

ii. One raingauge for 250 sq. km. to 400 sq.km. for moderate elevation (upto 1000 m a.s.l)

iii. One raingauge for 130 sq.km. for hilly areas and areas of heavy rainfall.

The Indian Standard and Indian Meteorological Department (1972) had recommended a simple formula, which was suggested by Rysoft (1949) to calculate the optimum number of raingauge stations to be established given by

$$N=(C_v/P)^2 \qquad \ldots\ldots(2.1)$$

Where

N = optimum number of raingauge stations to be established in the basin

C_v = Coefficient of variation of the rainfall of the existing rain gauge station (say, n)

P = desired degree of percentage error in the estimate of the average depth of rainfall over the basin.

Linsley et al (1947) had presented a U.S. weather Bureau graph. Which suggested that the standard error of estimate of storm rainfall over Muskingum basin in chicago, USA (CA = 8000 mi^2) was about 6 percent for a density of one raingauge per 100 mi^2 (about 250 km) and about 14 percent for a density of one raingauge per 500 mi^2 (about 1250 km).

Huff and Neill (1957) carried out a study of aerial variability of rainfall in a region characterized by thunder storm activity in Illinois state, USA.

Hershfield (1965) analysed rainfall data for 15 storm for each of 15 watersheds with a total of 400 raingauges and found that plots of correlation around key gauges showed evidence of anisotropy. No functional form were suggested. He suggested that the spatial correlation between gauges should not be less than some arbitrarily chosen level i.e. 0.9 and derived average gauge spacings on this basis.

Caffey (1965) analysed the spatial correlation structure of annual rainfall from 1141 stations from the Western U.S. and South Western Canada with an average length of record of 54 years. The regional variation in inter-station correlation was found to be explained reasonably well by (20) which was fitted directly by least squares to the correlations between a central station and surrounding station in a region. Approximately 60 percent of the variation in inter-station correlation coefficient was explained by (20), and the effects of topography, general wind circulation and frontal activity upon the orientation of the axis of maximal correlation were noted.

Huff and Shipp (1969) carried out an extensive spatial analysis of rainfall from three dense raingauge networks in lllinois; data ranging from one minute rates to total storm, monthly and seasonal amounts were analysed. The effects of rain type, synoptic storm type and other factor on spatial correlation were studied. Correlation decay with distance was greatest for thunderstorms, rainshoewers and air mass storms, and least for steady rain and the passage of low pressure centres, Summer decay rates were also much greater than those in winter. Anisotropy in correlation contours was also observed and the direction of least decay was observed to coincide with preferred storm paths. No functional representations of spatial correlation were suggested.

Hutchinson (1969) analysed monthly and annual rainfall data from two areas in New Zealand, one relatively flat and the other with variable topography. Plots of correlation around key gauges showed distinct anisotropy for both areas as well as dependence of the rate of decay on topography. Correlation functions of the form (16) were fitted using regression in which additional terms were included to account for measures of topography (differences in elevation, exposure and aspect); however, the improvement in explained variance due to the inclusion of topographic variables was significant only for a number of calendar months. Further work by Hutchinson (1970) for the same areas showed a distinct relationship between relief and the magnitude as spatial correlation for a given distance for monthly rainfall.

Hendrick and Comer (1970) followed a similar procedure, but attempted to take account of anisotropy by centering gauges within ellipses corresponding to the 0.9 correlation contour.

Kagan (1966) had suggested a procedure for computing the error in estimation of aerial rainfall which could be used as a criterion for determining the optimum network density of raingauges.

Hall (1972) suggested a rational method for determination of key station network using the equation

$$P_a = C + A_1 X_1 + A_2 X_2 + A_3 X_3 + A_4 X_4 + \ldots\ldots\ldots + A_n X_n \qquad \ldots\ldots(2.2)$$

Where P_a is the rainfall to be estimated from the observed record at selected station $X_1, X_2, X_3, \ldots. X_n$ and $A_1, A_2, A_3, \ldots.. A_n$ are regression coefficients, C being a constant known as intercept.

Cislerova and Hutchinson (1972) used optimal point interpolation error for pairs of gauges (Gandin, 1965) as a basis of the raingauge network of Zambia aimed at bringing the density up to the WMO recommended standard of one gauge per 900 sq. km.

Delhomme and Delfiner (1973) used Universal Kriging to interpolate rainfall on a regular grid for a large storm over an arid region of Chad. They calculated the gain in accuracy in the estimation of mean rainfall during a storm resulting from setting a new fictitious gauge at a point within the basin.

Morin et al (1979) advocated the use of principal component analysis in conjunction with optimal interpolation as an approach to raingauge network design.

Crowford (1979) described an experimental design model which was developed to evaluate trade-offs involved in the optimal sampling of rainfall.

O'Connell et al (1978,1979) employed optimal estimation procedures in the redesign of a raingauge network for an area of about 10,000 sq.km. in the South of England. Root mean square errors of interpolation were calculated using the estimates of spatial auto correlation of daily and monthly rainfall.

Jones et al (1979) used the optimal estimation procedure for preparation of maps of root mean square error of point interpolation for suggesting procedures for determining the accuracy of estimation of aerial rainfall for any shape of area and any configuration of gauges.

Bastin et al (1984) used rainfall being modeled as a two dimensional random variable. the variance was minimized by using the Kriging technique. it was shown that the method could be used for the optimal selection of the raingauge locations in a basin.

Sreedharan and James (1983) used the spatial correlation technique proposed by Kagan for design of raingauge network. The number of raingauge stations required for estimating the aerial rainfall with a given accuracy were derived by stipulating two criteria.

(i) The accuracy with which the average rainfall may be obtained over a given area and

(ii) The accuracy of spatial interpolation.

Mehra (1986) had also used the Kagan's technique for determining the raingauge network using the same accuracy criteria as above.

3.0 PROBLEM DEFINITION

3.0 Problem Definition

The raingauge network design aims at finding out the number of raingauge stations required for water resources assessment and flood forecasting in the region. Since the data requirement depends upon the specific purpose, therefore, the appropriate criteria must used for design of hydrological network. There is considerable variation in hydrological and hydrometeorological variables in time as well as in space, which may be accounted for by establishing the observation stations at number of locations. However, the raingauge networks are seldom planned or designed, hence the development of raingauge network is haphazard and adhoc, generally catering to the immediate local needs of time specific problems. The problems of the network design can be summed up as:

i. Number of data acquisition points required,
ii. Location of data acquisition points,
iii. Duration of data collection from a network.

Raingauge networks are generally set up for

i. Climatological or water balance studies
ii. Flood forecasting and
iii. Weather modification evaluation

Bihar is a playground of many rivers, particularly in the alluvial belt. The average rainfall of the state 1,245 mm mostly occur during the monsoon months. North Bihar lies on the Ganga basin and is drained by the Ghaghra, the Gandak, the Burhi Gandak. North Bihar is severely affected by floods during the monsoon season due to severe storms and drainage congestion, which indicates the need for revamping the raingauge network. Further, for purposes of planning and design of new irrigation schemes, rail and road bridges and urban drainage schemes, it is essential to have a dense network of ordinary and self recording raingauges. Also for organising relief measures, the administration needs block-wise information of rainfall excess which is only possible by considering this aspect while designing the raingauge network.

4.0 DESCRIPTION OF STUDY AREA

4.0 Description of Study Area

The river Burhi Gandak is an important river system of the Ganga Sub-basin (Fig. 1), which is a part of the Ganga Brahmaputra-Meghna Basin. It lies between 84° 0' and 86° 30' east longitudes and 25° 25' and 27° 30' North latitudes. The northern part of this river system lying in west Champaran district of Bihar is hilly and of fairly dense mixed Jungle, the southern part is of alluvial Gangetic plain, flowing across the west and east Champaran, Muzaffarpur, Samastipur and Begusarai districts.

The total catchment area of the river system is about 12,500 sq. km. of which about 10,150 sq. km. lies in Bihar and the rest in Nepal. The catchment area of the Burhi Gandak river system lying in India constitutes only 1.18 percent of the total area of the Ganga sub-basin in the country. The districtwise break-up of the catchment area are

1.	West Champaran	2885 sq. km.
2.	East Champaran	2428 sq. km.
3.	Muzaffarpur	1577 sq. km.
4	Vaishali	311 sq. km.
5	Samastipur	1745 sq. km.
6.	Begu sarai	1045 sq. km.
7.	Khagaria	158 sq. km.
	Total	10,150 sq.km.

Agriculture is the most predominant land use covering about 73 percent of the total catchment area. Area under forest is about 7 percent and the rest 20 percent caters to

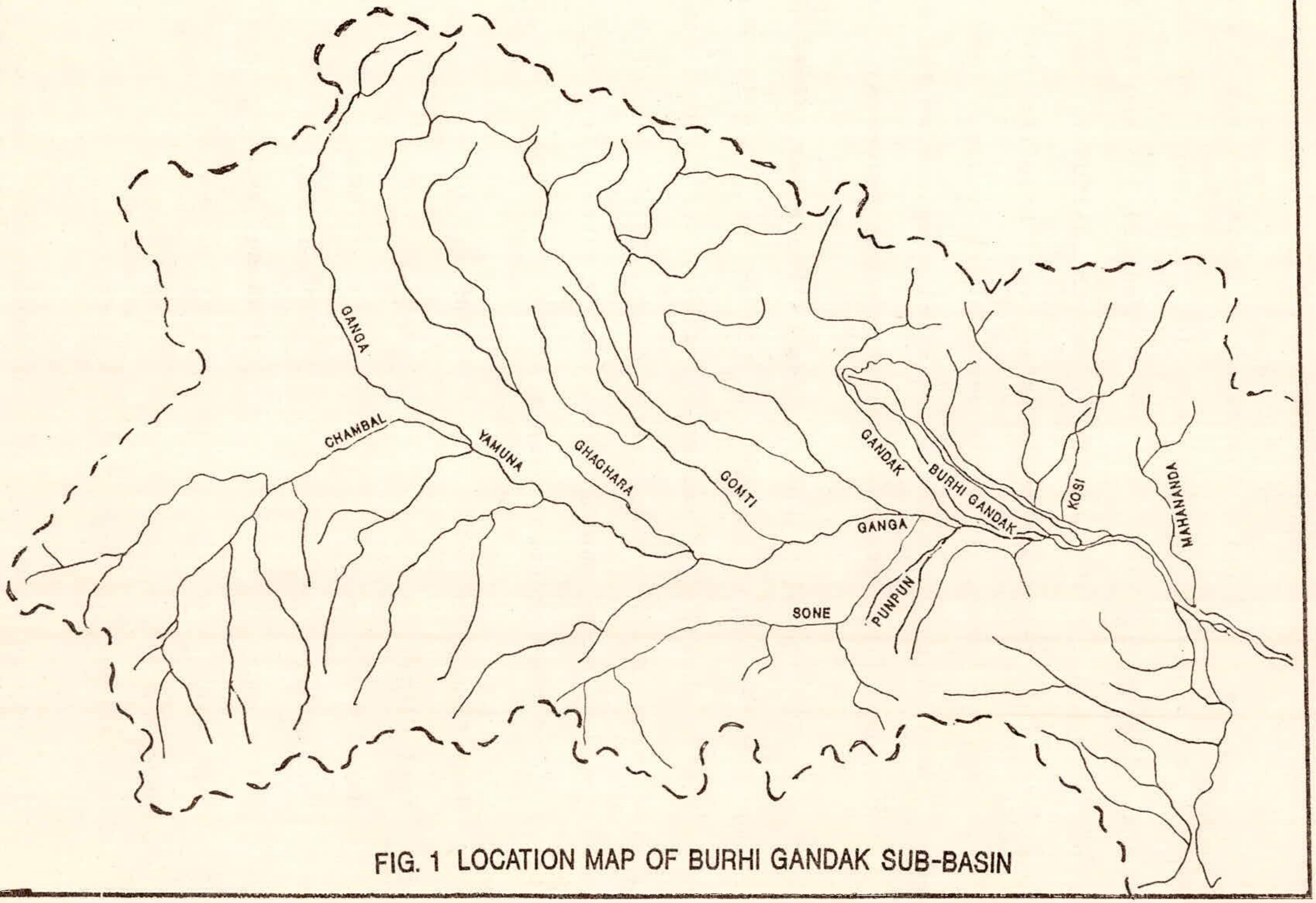

FIG. 1 LOCATION MAP OF BURHI GANDAK SUB-BASIN

miscellaneous purposes.

The catchment receives rainfall due to the effect of monsoon currents. Heavy rainfall in the catchment occurs during south-West monsoon. The basin gets about 83 % of its annual rainfall during period of four months i.e. middle of june to middle of october. The annual rainfall varies from 1141 mm to 1610 mm with mean rainfall of 1294.5 mm

There are 17 raingauge stations in the basin being maintained by the India Meteorological Department and State Irrigation Department. While, the data of only 15 raingauges existing in the basin could be collected from Bihar State Irrigation Department. These raingauge station are shown in the Location map (Figure 2) and the list of raingauge stations with their location is given in Table 1.

Table 1. List of Raingauge Stations with Location

Sl.No.	Station	Location	
		Lat.	Lon.
1.	Madhuban	26° 28'	85° 08'
2.	Samastipur	25° 52'	85° 48'
3.	Begusarai	25° 26'	86° 09'
4.	Motihari	26° 40'	84° 55'
5.	Minapur	26° 15'	85° 20'
6.	Shahibganj	26° 18'	86° 56'
7.	Mungheyr	25° 23'	86° 28'
8.	Khagaria	25° 30'	86° 29'
9.	Barhawa	27° 14'	84° 38'
10.	Ramnagar	27° 10'	84° 19'
11.	Lauria	26° 59'	84° 24'
12.	Muzaffarpur	26° 07'	85° 24'
13.	Bettiah	26° 48'	84° 30'
14.	Rosera	25° 45'	86° 02'
15.	Dalsinghsarai	25° 40'	85° 50'

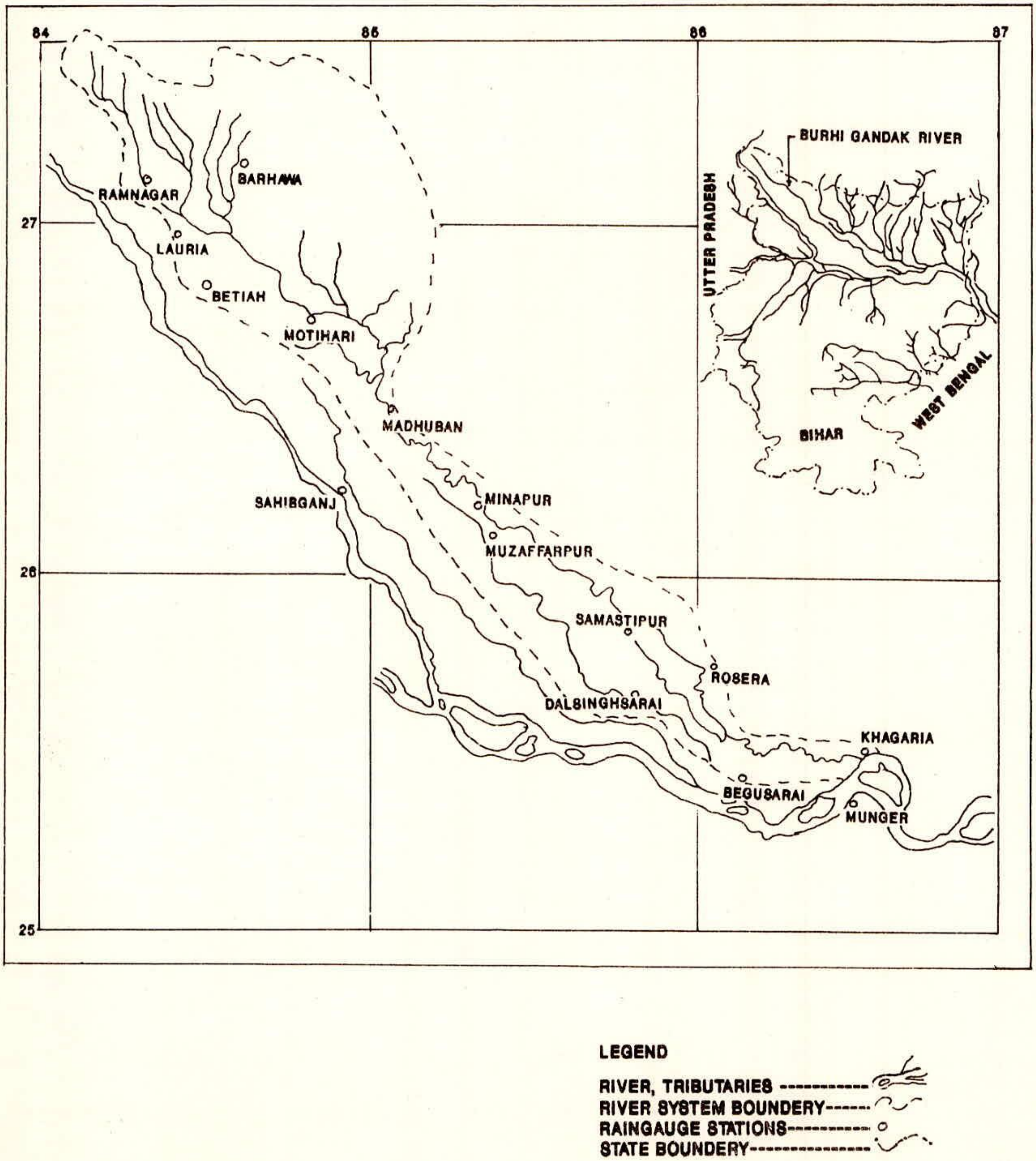

FIG. 2. RAINGAUGE STATIONS IN BURHI GANDAK SUB-BASIN

5.0 METHODOLOGY

5.0 Methodology

An attempt has been made for network design of raingauges considering two contingencies namely the requirement of gauges from (i) Climatological and (ii) hydrological considerations. Besides the criteria laid down by the World Meteorological Organisation (1974) and Indian Standard Institute (ISI 4987-1968) on the basis of area, other techniques like $(C_v/P)^2$, Kagan's technique in which error is computed in estimation of aerial rainfall for determining the network density of raingauges and Hall's method (1972) of key raingauge network by the simple correlation analysis have been used for the raingauge network design.

5.1 Optimal Raingauge Network Design

The formula for the determination of the optimum number of raingauges required using mean (normal) rainfall at each of the raingauges located in a given catchment is

$$N = (C_v/P)^2 \qquad \ldots\ldots(5.1)$$

Where

N = Optimum number of raingauge station to be established in the basin.

C_v = Coefficient of variation of the rainfall of the existing rain gauge stations.

P = Desired degree of percentage error in the estimate of the average depth of rainfall over the basin.

5.2 Kagan's Method

For estimating the number of raingauges using Kagan's method, a correlation function $\rho(d)$ as a function of the distance between raingauge station is considered. The form of function depends on the spatial variability of the rainfall and is expressed as

$$\rho(d)= \rho(o)\, e^{-d/d_o} \qquad ......(5.2)$$

Where $\rho(o)$ is the correlation corresponding to zero distance, and d_o is the correlation radius or distance at which the correlation is $\rho(o)/e$. Theoretically, $\rho(o)$ must be equal to 1, but due to microclimatic variations and the random errors in measurement of rainfall make $\rho(o)$ less than unity and the variance of these random errors is given by

$$\sigma_1^2=[1- \rho(o)]\sigma_h^2 \qquad ......(5.3)$$

Where σ_h^2 is the variance of precipitation time series at a fixed point.

The quantities $\rho(o)$ and d_o provide the basis for assessing the accuracy provided by a network. In this context, two accuracy criteria may be of interest :

Criteria 1: The accuracy with which the average rainfall over a given area may be obtained is to be evaluated. For an area s with a central station, and assuming $\rho(d)$ exists and is described by. eq.(5.2), the variance of the error in the average precipitation over s is given as :

$$V = \sigma_h^2 \; [\; 1- \rho(o)] + 0.23 \; \sigma_h^2 \sqrt{s}/d_o \qquad ......(5.4)$$

where the first term is attributed to random errors and is specified by eq. (5.3) and the second term is attributed to spatial variation in the precipitation field.

For an area S with n stations evenly distributed such that S = ns, the variance of the error in the average rainfall over S is given by

$$V_n = \frac{\sigma_h^2}{n} \left[1 - \rho(o) + 0.23 \; \frac{\sqrt{S}}{d_o \sqrt{n}} \right] \qquad ......(5.5)$$

The relative root mean square error is then defined as

$$Z_1 = \frac{\sqrt{V_n}}{\bar{h}} = C_v \; \frac{\sqrt{1- \rho(o) + 0.23 \; (\sqrt{S}/d_o \sqrt{n})}}{n} \qquad ...(5.6)$$

where $C_v = \sigma_h/\bar{h}$ and $\bar{h}$ is the average precipitation over S. From equation (5.6) the value of n required to meet a specified error criteria Z_1 can be obtained if the values of $\rho(o)$ and d_o are known, or conversely, given n, Z_1 can be evaluated.

The uniform spacing of stations over the area S such that S = ns can be achieved on the basis of a square grid for which the spacing between stations is :

$$1 = \sqrt{S/n} \qquad ......(5.7)$$

However, a triangular grid is usually more convenient if the area S has a complex configuration; the spacing is then given by :

$$1 = \sqrt{(2S/n\sqrt{3})} = 1.07 \sqrt{S/n} \qquad \ldots\ldots(5.8)$$

Criteria 2 : The accuracy of spatial interpolation is to be evaluated. Kagan (WMO,1972) has given the relative errors associated with linear interpolation between two points and interpolation at the centre of a square and a triangle, where the maximum errors of interpolation occur. For a triangular grid with spacing 1, the relative error is given by kagan as

$$Z_3 = C_v \sqrt{1/3[\ 1-\rho(o)] + 0.52\ \rho(o)/d_o\ (\sqrt{S/n})} \qquad \ldots\ldots(5.6)$$

assuming that (d) can be described by equation (5.2).

The derivation of Z_1 or Z_3 in a particular case requires the estimation of $\rho(d)$ from which $\rho(o)$ and d_o can in turn be derived. The function $\rho(d)$ can be evaluated by calculating the correlation ρ_{ij} between rainfall totals for a selected duration at stations i and j for all values of i and j, and then classifying the values of ρ_{ij} as a function of distance between stations. The value of ρ_{ij} is calculated as :

$$\rho_{ij} = \frac{\Sigma\, h_i h_j - [\ \Sigma h_i \Sigma h_j\ ]/m}{\sqrt{[\ \Sigma h_i^2 - (\Sigma h_i)^2/m]\ [\ h_j^2 - (h_j)^2/m]}} \qquad \ldots\ldots(5.7)$$

where the summations are taken from 1 to m and m is the number of pairs of observations. The determination of $\rho(o)$ and d_o then proceeds as follows :

(i) The correlation ρ_{ij}, $(i,j = 1,m)$ are classified into intervals on the basis of distance between stations;

(ii) The average distance and average correlation for the stations falling within each interval are then calculated;

(iii) Average distance is then plotted against average correlation, and an exponential curve is drawn through the points, as no details of a more objective procedure are given in the literature (of Kagan, WMO, 1972). The value of $\rho(o)$ is found by extrapolating $\rho(d)$ to zero distance, and d_o is calculated as the distance corresponding to a correlation of $\rho(o)/e$. Alternatively, $\ln[\rho(d)]$ may be plotted against d which should result in a linear plot with slope $-1/d_o$ and intercept $\ln[\rho(o)]$ on the basis of eq. (5.2). Objective fitting of a straight line to the ploted points by least squares, for example, might result in a value of $\rho(o)$ greater than unity which would be nonsensical. Consequently, a subjective approach such as fitting by eye is apparently the only alternative.

Thus permissible value of error Z can be known for a given number of raingauges n provided $\rho(o)$ and d_o are known. Vice-versa, the number of raingauges required for a desired percentage of error can be estimated.

5.3 Key Network design

In the process of determination of key station network as suggested by Hall, Correlation coefficient between the average of the storm rainfall and the individual station rainfall are found. The correlation coefficients are arranged in decreasing order. The station showing the highest correlation coefficient is called first key station. The station showing the highest correlation coefficient after removing the data of first station is called the second key station. Similarly, third, fourth etc. key station can be determined.

As each station gets added to the key station network the total amount of variance which accounted for by the network at that stage is determined. This provides a basis for determining the number of stations required for achieving an acceptable degree of error in the aerial estimate.

The multiple correlation coefficient increases with the increase of the number of station in the combination and the sum of the squares of the deviations of the estimated values of average rainfall from actual as well as the minimum deviation decreases till a stage is reached when improvement in either the multiple correlation coefficient or the sum of the square of deviations will be little. The corresponding number of raingauges at this stage is taken as the representative network for the purposes of determining aerial estimate of rainfall.

5.4 Location of the Raingauge Stations

Once the number of raingauges has been determined for the basin, selection of sites for the installations of raingauges is the next step. The selection must be considered at two levels:

(i) should the gauges be spaced to form the network and (ii) where should a gauge be placed in relation to its immediate surroundings?

The exact location of raingauge should be decided keeping in view the following points.

i. The raingauge station should be located near a village or town

ii. The site should be accessible throughout the year

iii. The distribution as a whole should be uniform over the catchment area (i.e. stations should be uniformly distributed between the isohytes).

iv. An far as possible each of the sub-catchment should be proportionate to the number of raingauge stations.

6.0 ANALYSIS

6.0 Analysis

The analysis of the annual rainfall data and storm rainfall has been carried out for estimation of number of raingauges required. Various methods used for the analysis are (i) World Meteorological Organization (WMO) criteria for determining minimum density of precipitation network. On the basis of geographical area ; (ii) $(C_v/p)^2$ technique and (iii) Kagan's technique for raingauge network on the basis of coefficient of spatial variation of rainfall and the expected error in the estimation of aerial rainfall and (iv) Hall's technique for key station network for the purpose of flood forecasting. The analysis has been carried out considering Burhi Gandak sub-basin as single unit with data of raingauges located in and around the sub-basin.

6.1 Computation of the mean annual rainfall

The rainfall data of various raingauge station operated by irrigation department in the Burhi Gandak sub basin is available only after 1973. Therefore, the short term means of the period 1974 to 1990 have been computed for each station. The mean annual rainfall for each raingauge station is given in Table 2. The rainfall pattern of the sub-basin was determined by plotting the hytographs (Fig. 3) of mean seasonal rainfall.

6.2 Raingauge Network Design

The analysis of rainfall data by various methods used for determining the number of raingauges required for the climatological and hydrological purpose is presented below.

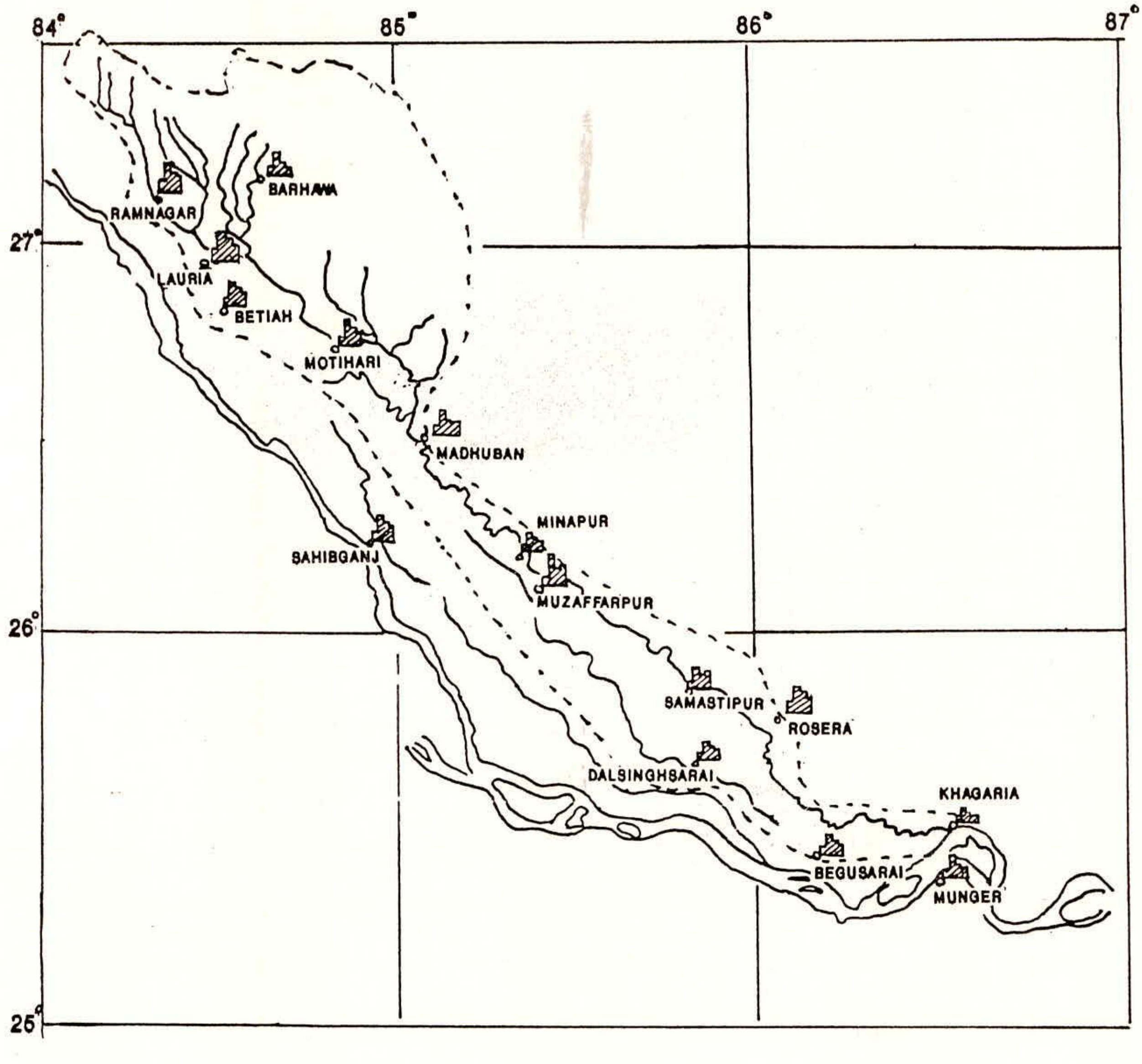

FIG 3. SEASONAL HYTOGRAPH MAP OF THE RAINGAUGE STATIONS IN BURHI GANDAK SUB-BASIN

6.2.1 Raingauge density considering geographical area

As a general guide to the density of precipitation station required, WMO gives the absolute minimum density for different parts of the World. As the aerial distribution of precipitation is more variable in mountainous areas, more gauges are needed to give an adequate sample. In India, the Indian Standard Institute and High Level Committee on floods set up by Government of India had suggested to establish minimum one station per 200 sq. miles. (518 sq. km.)

Table 2. Mean Annual Rainfall for Raingauge Stations

S.No.	Name of Raingauge Station	Short Term Mean Annual Rainfall
1.	Madhuban	1316.27
2.	Samastipur	1423.62
3.	Begusarai	1123.90
4.	Motihari	1463.78
5.	Minapur	1300.26
6.	Shahibganj	1395.86
7.	Mungheyr	1173.90
8.	Khagaria	943.31
9.	Barhawa	1191.38
10.	Ramnagar	1665.15
11.	Lauria	1483.49
12.	Muzaffarpur	1741.79
13.	Bettiah	1338.57
14.	Rosera	1373.17
15.	Dalsinghsarai	1203.53

The Burhi Gandak covers a catchment area of 10,150 sq.km. in India, mostly lying on the plains. Using the WMO criterion one raingauge per 900 sq.km. has been considered as appropriate. The total number of raingauges required in the sub-basin has been estimated by both WMO and Indian Standard criteria and presented in Table 3.

6.2.2 Spatial Variation Considerations

The optimum number of raingauge stations to be established in a basin is given by the Indian Meteorological Department (1972). An error criteria of 10% was recommended for estimation of the number of raingauges using $(C_v/P)^2$ formula. Raingauge networks for some specific purposes may require the use of a lesser error criteria. Therefore, the requirement of the number of raingauges has been made for 5% and 10% error criterion. The coefficient of variation (C_v) of annual mean rainfall for raingauge stations was calculated (C_v=0.152417). Considering the 5% and 10% error criterion and subsituting the calculated value of C_v in Eq. 5.1 the optimum number of raingauge stations were obtained as 10 and 3 respectively.

The Kagan's cross correlation technique has been used for the estimation of error in the aerial rainfall to be expected for a given number of raingauges. The distance between two raingauge stations is taken as the scalar measure of distance between two points in space (Table 4). The cross correlation coefficient of the annual rainfall data of the stations existing

Table 3. Raingauge Requirement in Burhi Gandak Sub-basin

Sub-basin/ District	Total geographical area		WMO Guidelines 900 sq.km. per raingauge	Standard prescribed in India 500 sq.km. per raingauge
	Hill	Plain		
Burhi Gandak Sub-basin	-	10,150	12	21
Districtwise area of the sub-basin				
West Champaran	-	2885	4	6
East Champaran	-	2428	3	5
Muzaffarpur	-	1577	2	4
Vaishali	-	311	1	1
Samastipur	-	1745	2	4
Begusarai	-	1045	2	2
Khagaria	-	158	1	1

Table 4. Distance between stations in space (km)

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. MADHUBAN	000														
2. SAMASTIPUR	55.90	000													
3. BEGUSARAI	93.39	37.64	000												
4. MOTIHARI	20.16	76.06	43.70	000											
5. MINAPUR	16.38	39.68	77.16	37.20	000										
6. SHAHIBGANJ	16.22	60.94	96.69	23.62	25.51	000									
7. MUNGHER	110.39	54.80	21.10	130.39	94.01	115.59	000								
8. KHAGARIA	104.40	49.61	21.73	124.40	88.19	110.55	9.29	000							
9. BARHAWA	62.20	117.32	154.96	43.30	78.11	66.14	170.86	163.78	000						
10. RAMNAGAR	70.87	126.93	164.25	50.87	87.40	70.08	181.89	175.12	20.00	000					
11. LAURIA	58.11	114.02	151.34	37.95	74.33	56.22	184.25	162.52	20.05	14.02	000				
12. MUZAFFARPUR	27.08	29.60	66.61	47.09	11.34	31.81	84.41	81.89	89.29	97.64	84.57	000			
13. BETIAH	46.14	101.57	138.58	26.77	62.36	26.93	156.38	150.55	30.55	27.87	13.70	71.97	000		
14. ROSERA	71.97	17.00	24.09	92.13	55.75	77.95	38.43	32.75	132.44	142.99	130.23	46.46	117.80	000	
15. DALSINGHSARAI	66.61	12.91	26.30	87.55	51.18	70.39	45.35	42.20	129.45	138.58	124.88	40.47	112.20	13.84	000

Table 5. Cross-correlation coefficients between various stations

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. MADHUBAN	1.000														
2. SAMASTIPUR	-.952	1.000													
3. BEGUSARAI	.112	.562	1.000												
4. MOTIHARI	.246	.516	.514	1.000											
5. MINAPUR	.068	.699	.007	.316	1.000										
6. SHAHIBGANJ	-.293	.557	.307	.529	.110	1.000									
7. MUNGHER	.470	.359	.273	.208	.446	-.480	1.000								
8. KHAGARIA	-.412	.797	.382	.367	.733	-.279	.526	1.000							
9. BARHAWA	-.575	.519	.393	.826	-.026	.286	.065	-.412	1.000						
10. RAMNAGAR	.429	.240	.187	.483	.394	.330	.227	.199	.543	1.000					
11. LAURIA	.368	.272	.263	.571	.598	.304	.150	.348	.317	.836	1.000				
12. MUZAFFARPUR	.030	.818	.412	.258	.627	-.012	.358	.034	.750	.185	.029	1.000			
13. BETIAH	-.373	.602	.058	.433	.413	.517	.199	.425	.656	.408	.182	.052	1.000		
14. ROSERA	-.782	.874	.651	.603	.228	.213	.298	.860	.504	.281	.333	.920	.428	1.000	
15. DALSINGHSARAI	-.686	.770	.469	.598	.257	.811	-.159	.618	.660	.324	.373	.984	.313	.663	1.000

in the sub-basin has been calculated (Table 5). The average distance and the average correlations for stations falling within an interval of 5km. have been determined (Table 6).

The interstation correlation has been plotted against interstation distance on a semi-log paper and presented in Fig 4 (Appendix-A). The value of $\rho(o)$ was taken from the logarithmic ordinate which is intercepted by the extrapolated straight line fitted by eye to the plotted points. It can be seen from the figure that the straight line intercepts the Y axis at 4.7, which is the value of $\rho(o)$. The value of $\rho(o)/e$ is calculated as 0.173 and the corresponding value of d_o is 190 km. Subsituting the values of C_v, $\rho(o)$, d_o and S (10,500 sq.km.), the relative error (Z_1) of mean areal rainfall and relative error of spatial interpolation (Z_3) were computed for different values of n (Table 7a and Table 7b) and then the graphs between Z_1 Verses n (Fig. 5) and Z_3 verses n (Fig. 6) were ploted.

6.2.3 Key Network of Raingauge Stations

The most rational method for determining the key station network is suggested by Hall (1972). In this method various storms (Table 8) were selected from available rainfall data and correlation coefficients between the average of the storm rainfall and the individual station rainfall were calculated. The stations were then arranged in the order of their decreasing correlation coefficient and the station exhibiting the highest correlation coefficient is called the first key station and its data is removed for determination of next key station.

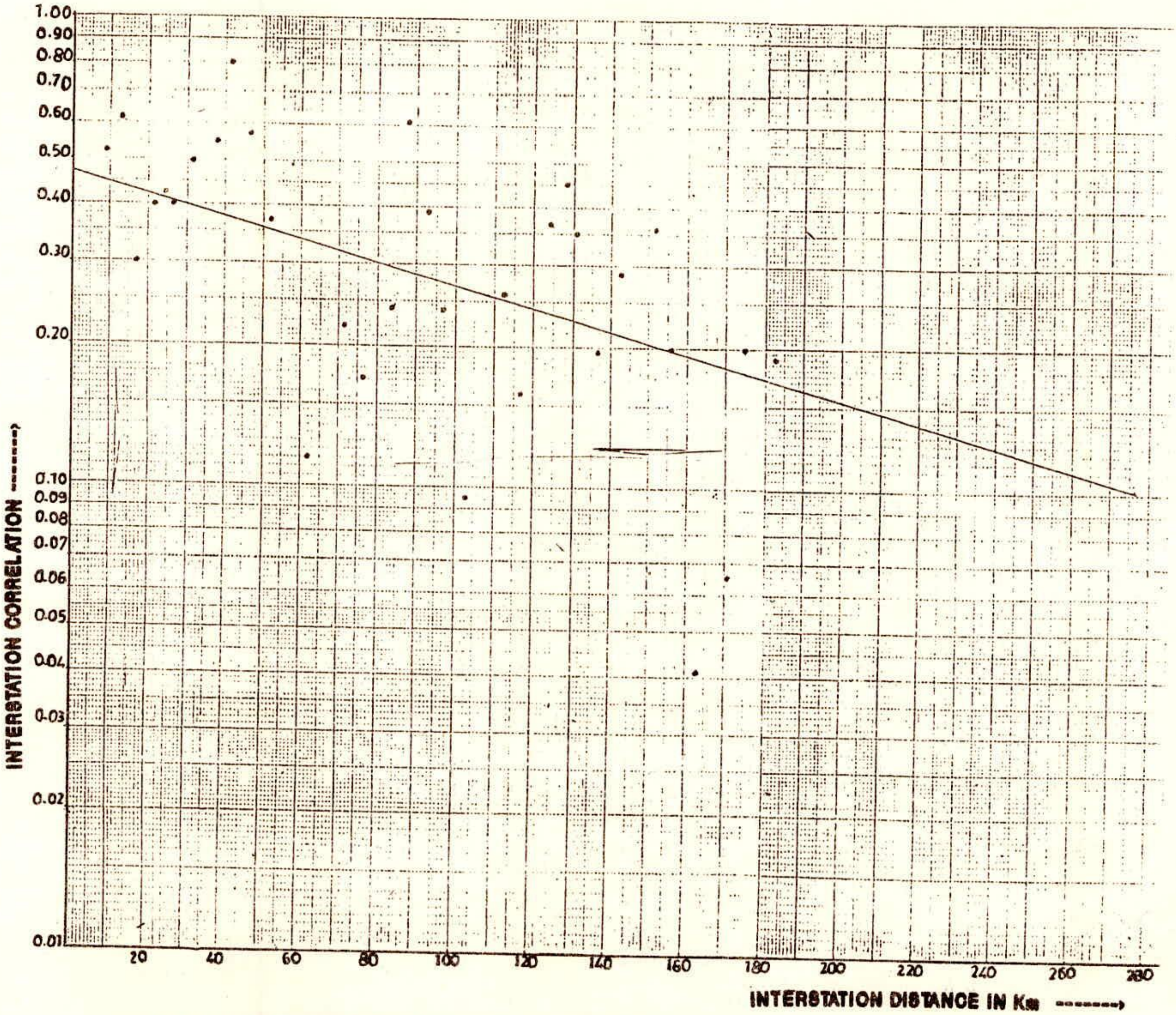

FIG.4 RELATIONSHIP BETWEEN INTERSTATION DISTANCE AND INTERSTATION CORRELATION

Table 6. Average Distance and Average Correlation Coefficient for Raingauge Stations in Buri Gandak Sub-basin

Distance Class Km	Mean Distance Km	Number of Cases	Mean Correlation Coefficient
0 - 5	-	NIL	-
5 - 10	9.29	1	0.5260
10 - 15	13.162	5	0.6156
15 - 20	17.40	4	0.2980
20 - 25	21.625	6	0.3997
25 - 30	27.151	7	0.3978
30 - 35	31.700	3	0.5013
35 - 40	38.180	5	0.5516
40 - 45	41.990	3	0.8090
45 - 50	46.930	5	0.5692
50 - 55	52.280	3	0.3663
55 - 60	56.495	4	-0.0130
60 - 65	61.830	3	0.1316
65 - 70	66.453	3	0.0040
70 - 75	71.602	6	0.2296
75 - 80	77.320	4	0.1775
80 - 85	83.623	3	0.2423
85 - 90	88.108	4	0.6187
90 - 95	93.177	3	0.3870
95 - 100	97.165	2	0.2460
100 - 105	102.985	2	0.0950
105 - 110	-	NIL	-
110 - 115	112.188	5	0.2580
115 - 120	116.903	3	0.1550
120 - 125	124.640	2	0.3700
125 - 130	128.190	2	0.4500
130 - 135	131.020	3	0.3480
135 - 140	137.080	2	0.1910
140 - 145	142.990	1	0.2810
145 - 150	-	NIL	-
150 - 155	152.283	3	0.6300
155 - 160	156.380	1	0.1990
160 - 165	163.517	3	0.0410
165 - 170	-	NIL	-
170 - 175	170.860	1	0.0650
175 - 180	175.120	1	0.1990
180 - 185	183.070	2	0.1880

Table 7a. Values of Z_1 for a given n

n	Z_1%	n	Z_1%
1	12.349	16	2.859
2	8.486	17	2.772
3	6.838	18	2.691
4	5.875	19	2.618
5	5.254	20	2.550
6	4.750	21	2.487
7	4.384	22	2.425
8	4.089	23	2.374
9	3.847	24	2.323
10	3.643	25	2.275
11	3.468	26	2.230
12	3.316	27	2.187
13	3.182	28	2.146
14	3.063	29	2.109
15	2.955	30	2.073

Table 7b. Values of Z_3 for a given n

n	Z_3%	n	Z_3%
1	8.48	16	6.990
2	7.93	17	6.974
3	7.677	18	6.958
4	7.521	19	6.945
5	7.412	20	6.933
6	7.331	21	6.920
7	7.267	22	6.910
8	7.215	23	6.899
9	7.171	24	6.889
10	7.135	25	6.880
11	7.102	26	6.872
12	7.076	27	6.862
13	7.050	28	6.855
14	7.029	29	6.848
15	7.010	30	6.840

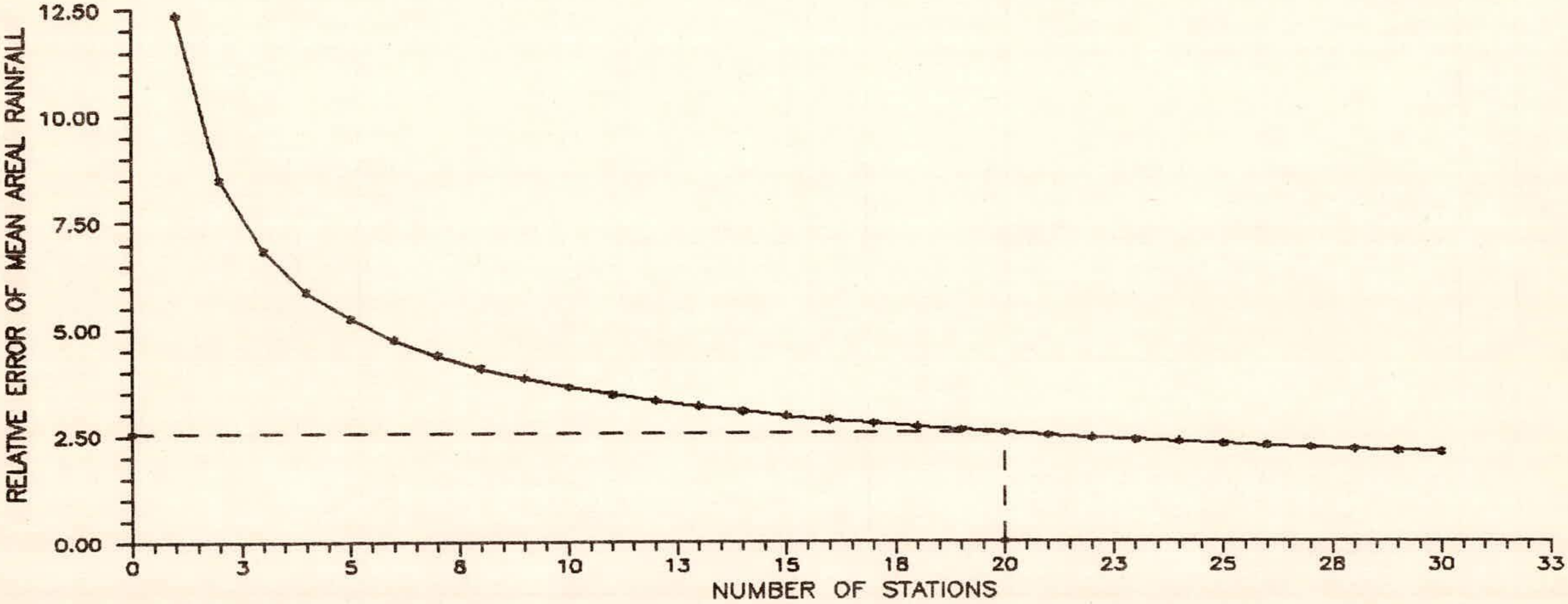

FIG 3. RELATIONSHIP BETWEEN RELATIVE ERROR OF MEAN AREAL RAINFALL AND NUMBER OS STATIONS

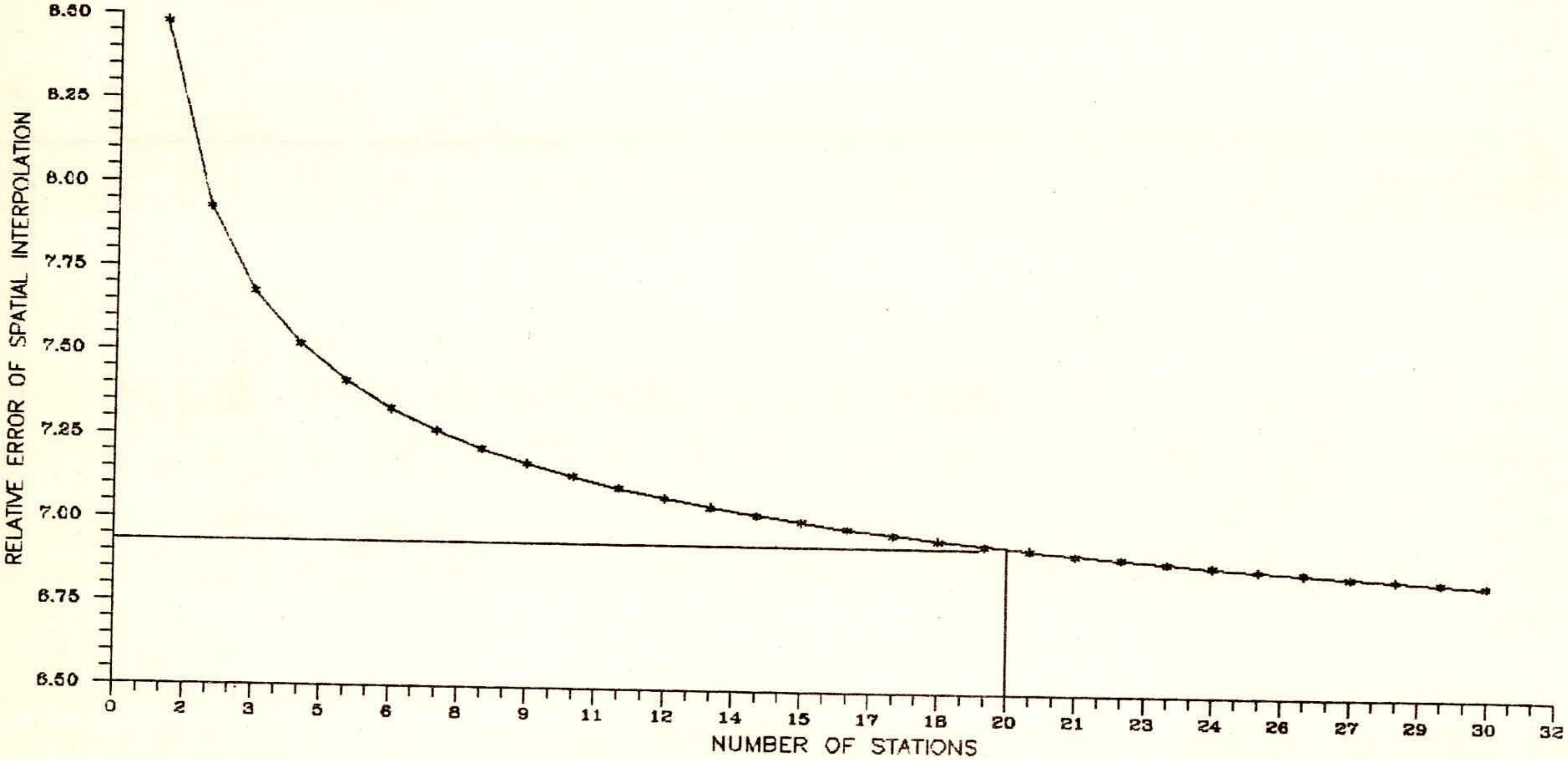

FIG 6. RELATIONSHIP BETWEEN RELATIVE ERROR OF SPATIAL INTERPOLATION (Z_3) AND NUMBER OF STATIONS

Table 8. Total rainfall in Different Storms in mm.

Sl. No.	Name of Rainfall Stations	Storm													
		1	2	3	4	5	6	7	8	9	10	11	13	14	15
1.	Mungheyr	509.40	104.40	194.30	132.00	428.50	315.70	95.20	164.20	210.60	88.40	432.50	106.20	115.80	112.00
2.	Rosera	99.50	118.00	89.00	158.00	406.00	271.30	173.00	171.60	572.20	210.70	806.40	591.50	156.00	27.00
3.	Samastipur	201.70	670.90	205.90	89.50	221.30	114.30	113.00	60.50	390.70	133.00	368.60	194.00	151.80	123.30
4.	Minapur	122.50	303.30	69.30	48.50	114.70	191.60	184.70	287.00	251.40	340.00	622.00	101.60	102.50	43.30
5.	Dalsinghsarai	57.00	241.00	84.50	107.00	158.90	199.20	228.00	153.00	338.90	122.50	346.00	163.40	126.00	42.00
6.	Bettiah	92.00	612.80	135.80	152.30	197.10	178.20	238.00	276.60	401.70	232.70	479.70	136.90	105.10	46.40
7.	Motihari	639.50	24.50	53.60	162.20	453.00	159.40	75.20	179.20	522.90	461.50	599.30	158.80	185.70	251.00
8.	Ramnagar	361.20	42.00	101.90	182.30	267.80	166.00	192.90	138.60	365.30	403.00	408.50	142.50	154.20	167.00
9.	Shahibganj	213.30	750.00	101.50	211.50	752.00	339.10	402.50	149.00	431.00	233.00	148.90	187.60	101.00	75.50
10.	Khagaria	189.20	328.00	79.00	98.70	162.10	80.20	73.50	62.80	412.60	251.70	405.60	380.80	58.60	141.20
11.	Muzaffarpur	00.00	90.50	26.60	93.00	223.30	46.00	88.20	44.70	331.50	180.50	344.90	370.20	74.10	73.00
12.	Lauria	96.80	84.30	78.60	212.30	168.60	99.90	99.00	251.00	423.70	227.80	403.20	290.20	17.50	30.90
13.	Begusarai	316.10	97.80	105.10	162.60	329.80	360.50	112.80	219.00	468.80	279.70	466.80	297.50	157.80	74.00
14.	Madhuban	106.20	696.90	123.80	28.10	308.80	245.40	126.00	198.00	506.40	176.00	657.00	308.20	136.80	254.80
15.	Barhawa	00.00	630.50	197.80	95.00	282.40	138.00	41.90	141.00	331.20	310.70	542.90	304.00	93.20	32.00
Total Rainfall		3004.40	4794.90	1646.70	1933.00	4474.30	2904.80	2243.90	2496.20	5958.90	3651.20	7032.30	3733.40	1736.10	1493.40
Average Rainfall		200.29	319.66	109.78	128.87	298.29	193.65	149.59	166.41	397.26	243.41	468.82	248.89	115.74	99.56

The process is repeated by considering the average rainfall of the remaining stations. The station showing the highest correlation coefficient after removing the data of first station was called the second key station. similarly, the third and fourth key stations were selected after removing the data of already selected stations (Appendix A). The sequences of the key stations so obtained is given in Table 9.

Table 9. Sequence of Key Stations Obtained

Sl.No.	Key Station
1.	Mungheyr
2.	Rosera
3.	Samastipur
4.	Minapur
5.	Dalsinghsarai
6.	Bettiah
7.	Motihari
8.	Ramnagar
9.	Shahibganj
10.	Khagaria
11.	Muzaffarpur
12.	Lauria
13.	Begusarai
14.	Madhuban
15.	Barhawa

In the next step the various combinations of stations i.e. 1st; 1st and 2nd; 1st, 2nd and 3rd; 1st, 2nd, 3rd and 4th etc. were considered to constitute the key network and multiple correlation coefficient were calculated for each case. The multiple correlation coefficient more or less increases with addition of raingauge stations to the key network (Table 10). It is seen that the coefficient in respect of Motihari is always negative, which is physically not justified and therefore it was removed for the calculation of multiple correlation coefficient.

Table 10. Coefficeint of the Regression Equation

Combination	Mungheyr	Rosera	Samastipur	Minapur	Dalsinghsarai	Betiah	Motihari	Ramnagar	Shahibganj	Khagaria	Muzaffarpur	Lauria	Intercept	MCC
1	0.712158												85.73589	0.84117
2	0.420752	0.247331											74.02335	0.86162
3	0.184837	0.239388	0.196804										67.99856	0.92377
4	0.245088	0.162823	0.135299	0.250913									51.93908	0.92377
5	0.223723	0.103031	0.135477	0.253680	0.085925								52.84202	0.91768
6.	0.150672	0.110809	-0.026602	0.192718	0.163822	0.367396							11.82014	0.96319
7.	0.163256	0.110145	-0.020246	0.157467	0.139377	0.343235	0.055286						14.20939	0.95930
8	0.025106	0.063236	0.023498	0.399637	0.252982	0.081480	-0.063224	0.196323					8.57776	0.98812
9	0.007270	0.057743	0.113346	0.120060	0.150103	0.094054	-0.098443	0.183693	0.228921				12.93778	0.99125
10	0.009301	0.056846	0.115532	0.122580	0.151340	0.092105	-0.099143	0.184247	0.227531	-0.005144			13.00598	0.98833
11	0.123823	0.040108	0.173444	0.086871	0.103574	0.037952	0.009476	0.154338	0.129161	-0.102693	0.706240		12.58103	0.99873
12	0.096046	0.084072	0.213086	-0.043963	0.073997	0.051557	-0.029562	0.088430	0.195249	0.124321	0.066485	0.126283	7.44129	0.99866

Table 11. Coefficient of Regression Equation after Removing Station Motihari

Combination	Mungheyr	Rosera	Samastipur	Minapur	Dalsinghsarai	Betiah	Motihari	Ramnagar	Shahibganj	Khagaria	Muzaffarpur	Lauria	Begusarai	Intercept	MCC
1	0.712158													85.73589	0.84117
2	0.420752	0.247331												74.02335	0.86162
3	0.184837	0.239388	0.196804											67.99856	0.92377
4	0.245088	0.162823	0.135299	0.250913										51.93908	0.92377
5	0.223723	0.103031	0.135477	0.253680	0.085925									52.84202	0.91768
6	0.150672	0.110809	-0.026602	0.192718	0.163822	0.367396								11.82014	0.96319
7	0.054838	0.69133	0.02866	0.33638	0.216598	0.097032		0.169285						11.38287	0.98789
8	0.054082	0.06782	0.76041	0.149327	0.143428	0.109651		0.152831	0.136017					14.89846	0.98747
9	0.017086	0.08074	0.04598	0.106624	0.124821	0.138421		0.147591	0.168113	0.080506				13.61280	0.98505
10	0.118664	0.03961	0.17451	0.089155	0.106888	0.037895		0.157475	0.136226	-0.102908	0.067682			12.56842	0.99911
11	0.115224	0.06388	0.19311	0.615192	0.084089	0.045195		0.115971	0.155730	-0.113848	0.071891	0.06660		9.88520	0.99912
12	0.835975	0.09804	0.21485	-0.186618	0.009044	0.100687		0.032824	0.233418	-0.044959	0.065423	0.18564	0.6583	3.78241	0.99850

MCC - Multiple correlation coefficient

The multiple correlation coefficient for different combinations of stations along with the coefficient of the respective regression equations and their intercepts are presented in Table 11. A graph between the multiple correlation coefficient and corresponding number of stations in each combination of representative station has been plotted (Fig 7). As may be seen from the graph that there is no improvement in the multiple correlation coefficient with the increase of station in the network after the 7th station. Therefore, 7 raingauge stations (Table 12) have been suggested for key station network for flood forecasting purpose.

Table 12. Sequence of Key Stations Obtained from the Graph between Multiple Correlation Coefficient and Number of Stations

Sl.No.	Key Station
1.	Mungheyr
2.	Rosera
3.	Samastipur
4.	Minapur
5.	Dalsinghsarai
6.	Bettiah
7.	Motihari

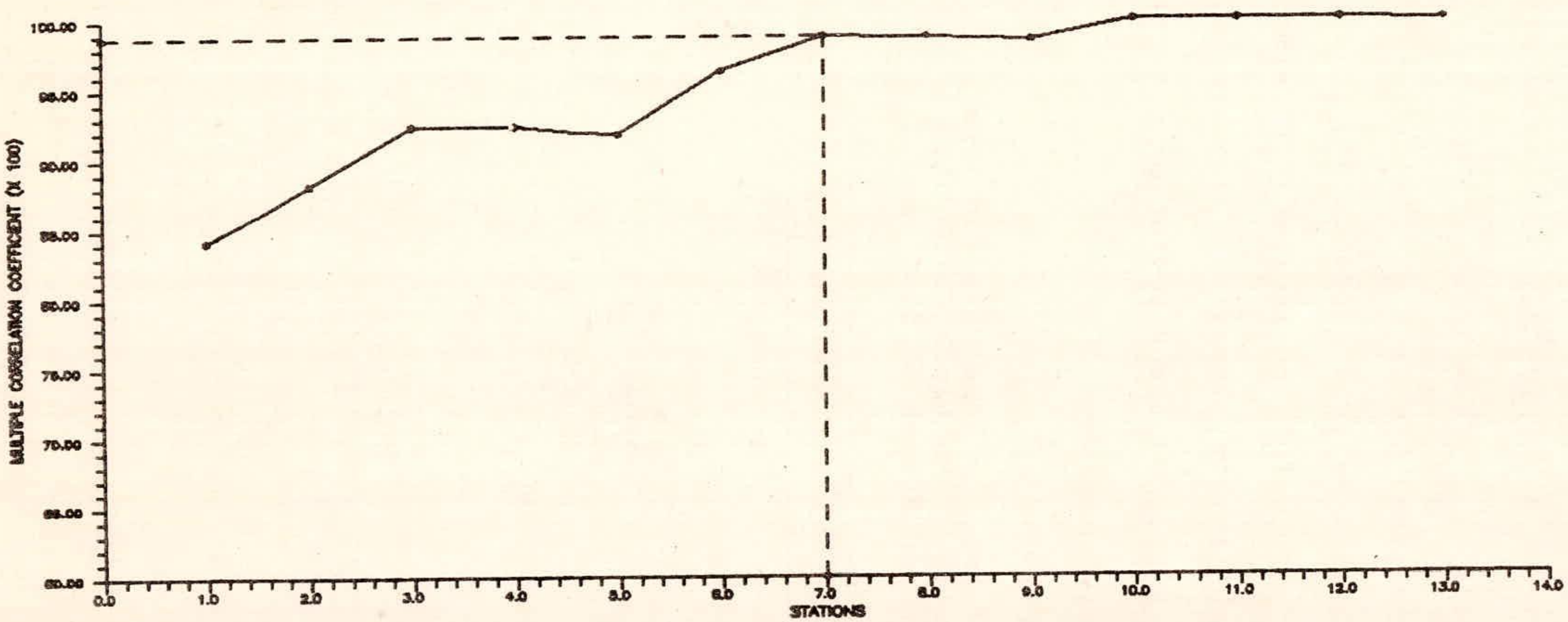

FIG. 8 RELATIONSHIP BETWEEN MULTIPLE CORRELATION COEFFICIENT AND STATIONS

6.2.4 Self Recording Raingauges

The large scale flooding of Burhi Gandak sub-basin has emphasised the need to have self recording raingauge stations. As per the norms of IMD, 10% of the raingauges present in the catchment should be Self Recording Rain Gauges(SRRG), which accounts for presence of at least one or two SRRG.

7.0 RESULTS

7.0 RESULTS

Short term mean of the rainfall data of various station were calculated. From Table 2, it can be seen that mean annual rainfall varies from 943.31 to 1741.79. The value of mean annual rainfall is minimum at Khagaria and maximum at Muzzafarpur. The seasonal rainfall hytograph of the raingauge stations in the basin indicates that the rainfall pattern is almost uniform.

The requirement of additional raingauges in Burhi Gandak sub-basin is nil according to WMO guidelines (Table 3). While, 6 additional raingauges are required according to India standard criterion. By using $(C_v/P)^2$ technique the optimum number raingauges for 5% and 10% error criterion comes out to be 3 and 10. The values of optimum number of of raingauges is quite less than the existing number of raingauges and therefore, the requirement of additional raingauges is nil. The relative error of mean aerial rainfall and spatial interpolation have been calculated by Kagan's method and given in Table 7a and Table 7b respectively. Which shows that the relative error of mean aerial rainfall is less than 10% for even 2 raingauges. While, considering 6 raingauges in the sub-basin the relative error is less than 5% (Fig.8). The relative error of spatial interpolation is less then 10% while considering one raingauge in the sub-basin

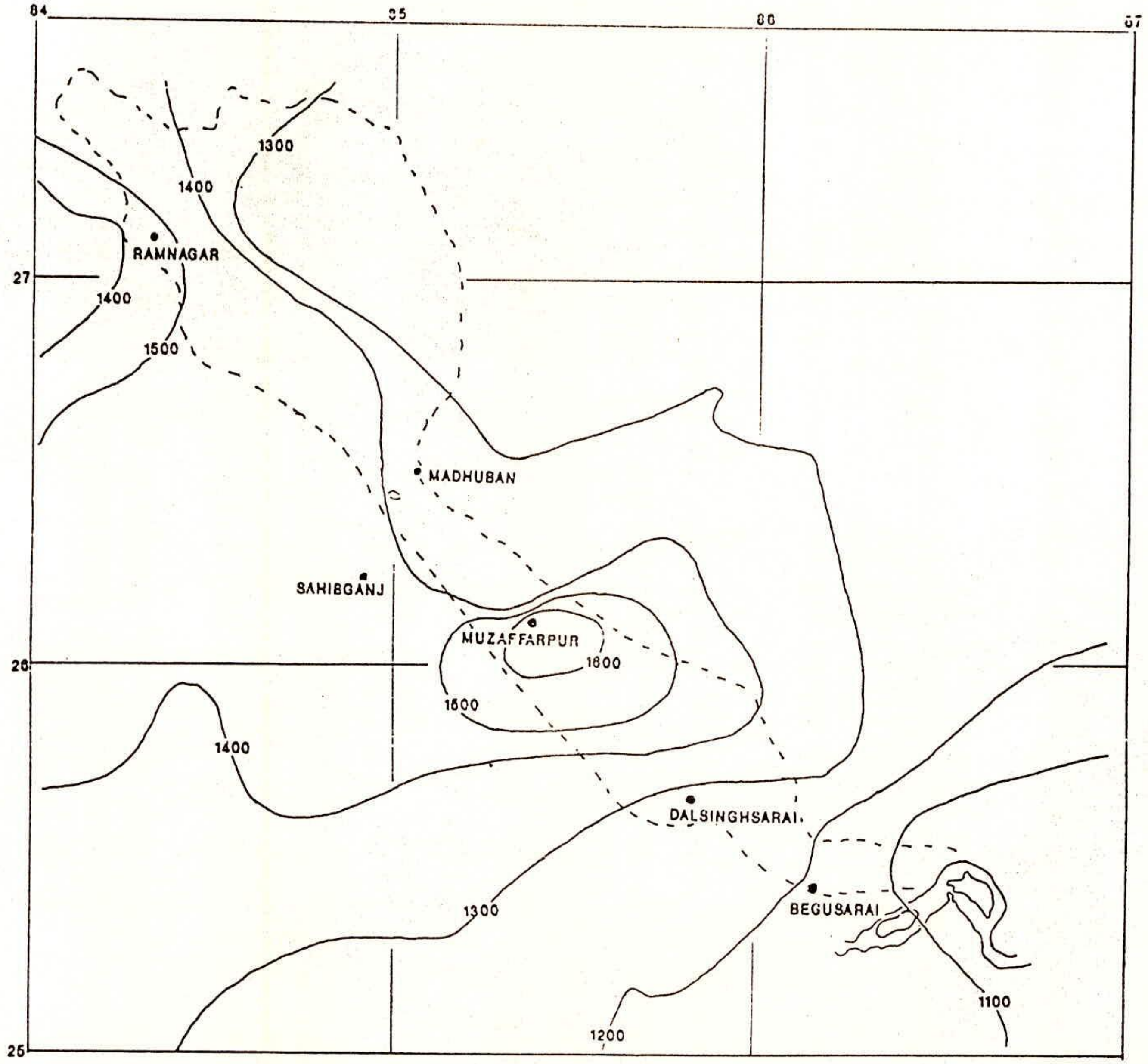

FIG 8. RAINGAUGE NETWORK BASED ON KAGAN'S METHOD

and it never comes to 5% even with 100 raingauges. It can be seen from Fig. 5 and Fig 6 that by the addition of raingauges in the network, the relative error of mean areal rainfall and spatial interpolation reduces. The addition of any raingauge after 20 raingauges causes almost negligible reduction in relative error. For flood forecasting purpose the key network of rainfall station has been determined by Hall's method. Sequence of the key stations given in table 9, shows that the Mungheyr is the first key station, while Barhawa is the last. For deciding the number of raingauges in key station network the multiple correlation coefficient has been calculated for different combination of raingauge stations (Table 10,11). The graph between multiple correlation coefficient and number of stations (Fig. 7) shows that addition of a raingauges after seven raingauges causes almost negligible increase in multiple correlation coefficient. Therefore, the first seven raingauges presented in table 9 were considered for key network design. The location of these Key stations is shown in figure 9.

The Indian Meteorological Department has fixed a norm that 10% of the total number of raingauge stations should be self- recording. According to which the requirement of self-recording raingauges comes out to be one or two.

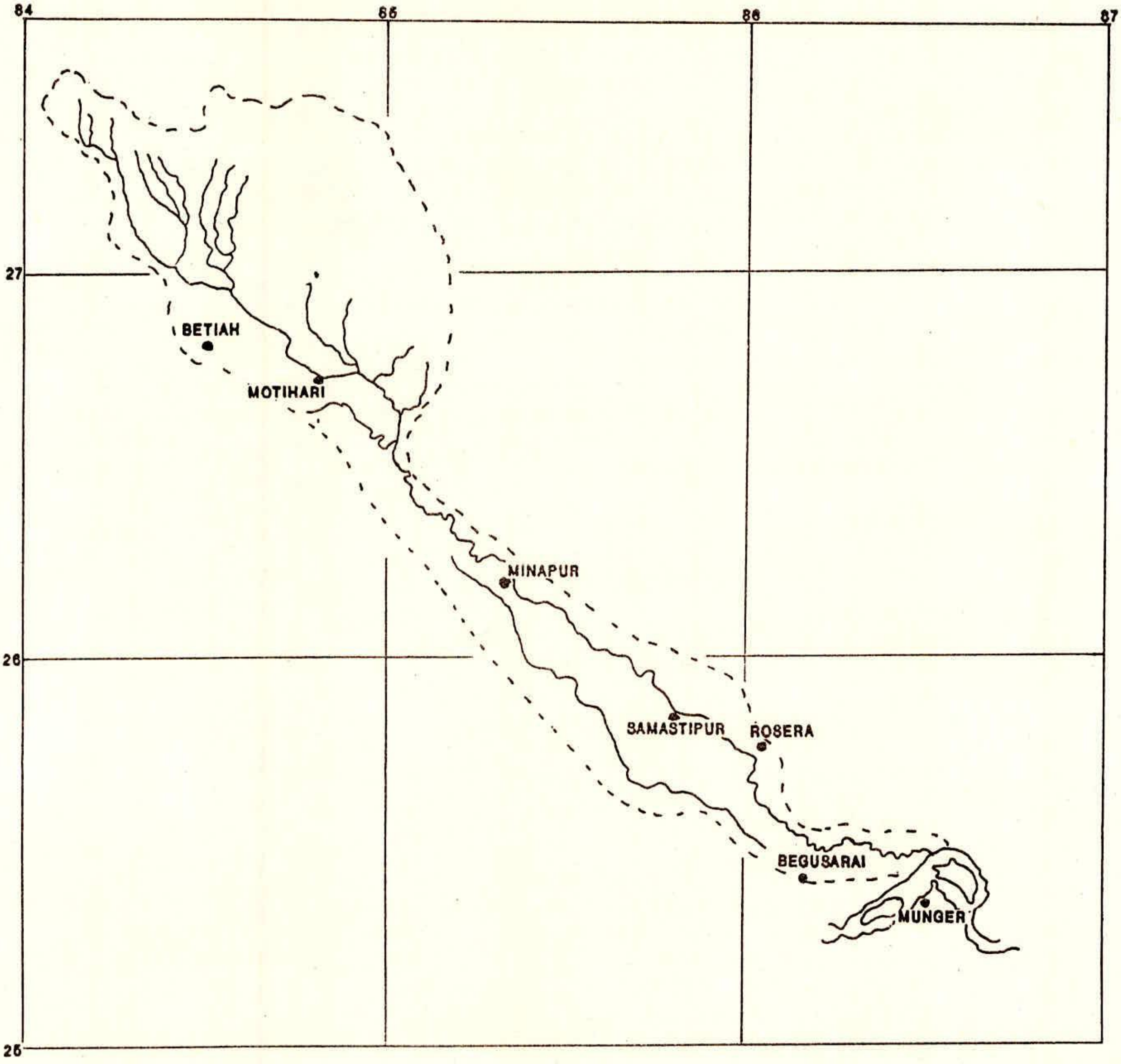

FIG 9.. MAP SHOWING THE KEY STATION NETWORK

8.0 CONCLUSIONS

8.0 CONCLUSIONS

It is found that the different methods used for raingauge network design give different results (Table 13). The number of stations obtained by WMO and $(C_v/P)^2$ technique are quite less than the existing number of raingauge stations in the Burhi Gandak sub- basin. Considering the 2 and 6 raingauges stations in Kagan's method the relative error of mean aerial

Table 13 Comparision of Different Methods of Raingauge Network Design

Sl. no.	Method of Network Design	Number Raingauge Required
1	Geographical area method	
	a) WMO Criterion	12
	b) Indian Standard Criterion	21
2	Optimal Network Design (by $(C_v/P)^2$)	
	i) $P = 5\%$	10
	ii) $P = 10\%$	3
3	Kagan's Method	
	a) Relative error of mean areal rainfall	
	i) $Z_1 = 5\%$	6
	ii) $Z_1 = 10\%$	2
	b) Relative error of spatial interpolation	
	i) $Z_3 = 5\%$	-
	ii) $Z_3 = 10\%$	1
4.	Key Network Design (Hall's Method)	7

rainfall comes out to be less than 10% and 5% respectively. While, the relative error of spatial interpolation is always less then 10%. This also indicates that the existing raingauges network is adequate. while the Indian standard criterion and Kagan's method considering minimum relative error (Fig. 5 & 6) of mean aerial rainfall, gives almost similar results. These two methods shows that atleast 5 more raingauges are required in the sub-basin. The IMD criterion shows the need of at least one or two self recording raingauges in the basin.

The key network design by Hall's method shows that the increase in the number of key stations in the network improves the multiple correlation coefficient. Seven number of raingauge stations namely Mungheyr, Rosera, Samastipur, Minapur Dalsinghsarai, Bettiah and Ramnagar can be taken for key station are identified for key station network.

It is also concluded that instead of adopting the only WMO or ISI guidelines which are based on geographical area for developing the raingauge network need base appropriate criteria to be adopted to meet the challenge of management of sub-basins.

8.1 Recommendation

The raingauge network design remains a cumbersome problem because of non agreement among hydrologists on the choice of network design method. It is deduced from the careful observation of various methods of design of raingauge network that the WMO guidelines and Indian standard criterion are based on geographical area; optimal raingauge network design by $(C_v/p)^2$ takes into account the coefficient of variation of rainfall, key station network considers the coefficient of correlation of storm data to locate key stations for operation during flood period and; Kagan's method considers both interstation distance and interstation correlation.

Thus, in estimating the raingauge network for Burhi Gandak sub-basin, no single method has been found to be uniformly superior to others. However, it is recommended that it would be appropriate to use the analysis provided by Kagan's method as it takes into account both interstation distance and interstation correlation.

The number of raingauge stations calculated by Kagan's method are less than the existing raingauge stations. Therefore, the redundant stations should be discontinued and the selection should be made without disturbing uniformity of distribution of stations between the isohyets.

As number of proposed projects are under investigation it would be desirable that all stations should be continued. This would provide necessary precipitation data, though, more than required. However, for a new project this would be useful information.

Keeping in view the hydrologic similarities of other basins in the region it is recommended that the Kagan's method should be applied for other river basins to prove its superiority over other methods.

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APPENDIX-A

Table : Coefficient of Correlation between the Storm Data for Various Stations and Average Rainfall

Station No.	Raingauge Station	Coefficient of Correlation
1.	Madhuban	.414
2.	Samastipur	.818
3.	Begusarai	.677
4.	Motihari	.760
5.	Minapur	.818
6.	Shahibganj	.759
7.	Mungheyr	.572
8.	Khagaria	.548
9.	Barhawa	.432
10.	Ramnagar*	.854
11.	Lauria	.756
12.	Muzaffarpur	.746
13.	Bettiah	.756
14.	Rosera	.842
15.	Dalsinghsarai	.805
1.	Madhuban	.433
2.	Samastipur	.815
3.	Begusarai	.668
4.	Motihari	.768
5.	Minapur	.824
6.	Shahibganj	.762
7.	Mungheyr	.574
8.	Khagaria	.550
9.	Barhawa	.443
11.	Lauria	.740
12.	Muzaffarpur	.740
13.	Bettiah	.761
14.	Rosera*	.837
15.	Dalsinghsarai	.799
1.	Madhuban	.462
2.	Samastipur*	.827
3.	Begusarai	.622
4.	Motihari	.762
5.	Minapur	.812
6.	Shahibganj	.729
7.	Mungheyr	.613
8.	Khagaria	.599
9.	Barhawa	.428
11.	Lauria	.747
12.	Muzaffarpur	.762
13.	Bettiah	.795
15.	Dalsinghsarai	.765

Station No.	Raingauge Station	Coefficient of Correlation
1.	Madhuban	.467
3.	Begusarai	.662
4.	Motihari	.767
5.	Minapur*	.795
6.	Shahibganj	.762
7.	Mungheyr	.616
8.	Khagaria	.596
9.	Barhawa	.475
11.	Lauria	.687
12.	Muzaffarpur	.720
13.	Bettiah	.761
15.	Dalsinghsarai	.775
1.	Madhuban	.486
3.	Begusarai	.658
4.	Motihari	.757
6.	Shahibganj	.745
7.	Mungheyr	.639
8.	Khagaria	.611
9.	Barhawa	.473
11.	Lauria	.679
12.	Muzaffarpur	.711
13.	Bettiah	.762
15.	Dalsinghsarai*	.771
1.	Madhuban	.546
3.	Begusarai	.593
4.	Motihari	.734
6.	Shahibganj	.687
7.	Mungheyr	.707
8.	Khagaria	.677
9.	Barhawa	.451
11.	Lauria	.664
12.	Muzaffarpur	.719
13.	Bettiah*	.806
1.	Madhuban	.517
3.	Begusarai	.640
4.	Motihari*	.741
6.	Shahibganj	.727
7.	Mungheyr	.678
8.	Khagaria	.647
9.	Barhawa	.487
11.	Lauria	.645
12.	Muzaffarpur	.690

Station No.	Raingauge Station	Coefficient of Correlation
1.	Madhuban	.541
3.	Begusarai	.643
6.	Shahibganj	.678
7.	Mungheyr*	.691
8.	Khagaria	.640
9.	Barhawa	.537
11.	Lauria	.649
12.	Muzaffarpur	.668
1.	Madhuban	.429
3.	Begusarai	.742
6.	Shahibganj*	.788
8.	Khagaria	.471
9.	Barhawa	.646
11.	Lauria	.646
12.	Muzaffarpur	.640
1.	Madhuban	.515
3.	Begusarai	.661
8.	Khagaria	.546
9.	Barhawa	.628
11.	Lauria*	.678
12.	Muzaffarpur	.642
1.	Madhuban	.579
3.	Begusarai	.684
8.	Khagaria	.517
9.	Barhawa*	.690
12.	Muzaffarpur	.533
1.	Madhuban	.673
3.	Begusarai	.547
8.	Khagaria*	.725
12.	Muzaffarpur	.699
1.	Madhuban	.632
3.	Begusarai*	.698
12.	Muzaffarpur	.647
1.	Madhuban*	.796
12.	Muzaffarpur	.733
12.	Muzaffarpur*	1.000

* indicates the station having maximum correlation

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